

The Brighter-Fatter and other Sensor Effects in CCD Simulations for Precision Astronomy

C.W. Walter

Department of Physics, Duke University

Durham, NC 27708, USA

E-mail: `chris.walter@duke.edu`

ABSTRACT: Upcoming and current large astronomical survey experiments often seek to constrain cosmological parameters via measurements of subtle effects such as weak lensing, which can only be measured statistically. In these cases, instrumental effects in the image plane CCDs need to be accounted and/or corrected for in measurement algorithms. Otherwise, the systematic errors induced in the measurements might overwhelm the size of the desired effects. Lateral electric fields in the bulk of the CCDs caused by field shaping potentials or space charge build up as the electrons in the image are acquired can cause lateral deflections of the electrons drifting in the CCD bulk. Here, I report on the LSST effort to model these effects on a photon-by-photon basis by the use of a Monte Carlo technique. The eventual goal of this work is to produce a CCD model validated by laboratory data which can then be used to evaluate its effects on weak lensing science.

KEYWORDS: Photon detectors for UV, visible and IR photons (solid-state) (PIN diodes, APDs, Si-PMTs, CCDs, EBCCDs etc); Detector modeling and simulations II (electric fields, charge transport, multiplication and induction, pulse formation, electron emission, etc).

Contents

1. Introduction	1
2. The Brighter-Fatter Effect	2
2.1 Spots	3
2.2 Flats	3
2.3 Brighter Fatter Effect Conclusions	5
3. Edge Effects	6
4. Tree Rings	9
5. Conclusions	9

1. Introduction

A requirement in the design of detectors and associated measurement algorithms in next generation survey instruments is that the systematic errors caused by instrumental effects in the image plane CCDs are not themselves larger than the size of the signals being measured. This is especially important in weak lensing analyses which rely on careful measurements of PSF-convolved galaxy shapes. A particular concern in these analyses is the effect of electric fields in the bulk of the CCDs, which can cause lateral deflections of the electrons as they drift through the sensor.

In the LSST project [1] we are using a Monte Carlo approach to try to simulate physical effects in the sensors. PhoSim [2, 3] is a photon-by-photon tracking simulation package for optical telescopes. It can follow photons through the atmosphere, into and through the optics of the telescope and finally into the image plane itself where the photon’s interactions with the silicon are modeled and the resulting electrons are tracked through the CCD and collected to form pixelized images. The goal of this work is to understand and control the instrument based systematic errors which might affect the extraction of cosmological parameters in the LSST science analysis.

The overall LSST strategy is that, whenever possible, we will always employ a physics-based model for the effects in the instrument including electron-by-electron tracking. Driving this philosophy is a desire to not trivially simulate and then correct for instrumental effects with similar parameterized models. By relying on physics-based models which we have validated with real data taken in the lab we can evaluate our correction and measurement algorithms.

At this point in our studies, we usually turn one instrumental effect on at a time with everything else turned off. We often magnify the effects in order for us to understand them and we vary their size in order to match the observed magnitudes in the laboratory. Finally, running and tracking each electron separately can be quite time-consuming. For these reasons, time-savings measures

are sometimes employed during the simulation runs. For example, we sometimes reduce the size of the simulated CCD chips by up-to a factor of ten.

In this talk, I will focus on the simulation and validation of some of the main sensor effects that are currently implemented in PhoSim. Specifically, I will focus on the so-called Brighter-Fatter effect in which charge already collected in a pixel is believed to deflect later arriving drifting electrons into adjacent pixels, thereby modifying both the expected spot size as a function of height and the expected relationship between the mean pixel occupancy and its variance in a flat illumination. I will also discuss the behavior of charge as it approaches the edge of the sensor. Finally, in this talk I will discuss the work done by Andrei Nomerotski and Ben Beamer on the effect of “Tree-Ring” like doping inhomogeneities in the silicon boules. You can find this work described in Mr. Beamer’s contribution to these proceedings [4].

2. The Brighter-Fatter Effect

The Brighter-Fatter (BF) effect is now a well described phenomenon that has been seen by many groups, and several have produced models to describe it [5, 6, 7, 8]. Recently, the DECam team has begun to characterize and correct for the effect in their analyses [9, 10]. As described above, the BF effect is modeled as a consequence of the space-charge which has already been collected in the pixels of the CCD. As the next electron follows the field lines down to the collection area the charge already in the pixel deflects the electron horizontally. One can also think of this problem as an effective mapping between the effective pixels on the surface of the CCD and the pixels in the charge collection area. The presence of charge in the well can warp the effective pixel area on the surface, effectively reducing it as the modified field lines carry the charge to different pixels at the wells.

Importantly, the BF effect can also modify the expected relationship between the mean value and variance of the electron count in each well in flat illuminations of the sensor. Charge that might normally be in a well is diverted if there is already charge in that well thus disturbing the expected poisson statistics. This effect reduces the observed variance relative to the expectation. *A well motivated and implemented physical model should correctly simulate both the spot spreading and flat variance reduction effects with the same parameters.*

One of the main insights that came from the preparation of this talk was that currently, different groups are implementing the modification of the field lines in the CCD from collected charge differently. Currently, PhoSim solves for the static electrostatic fields by solving Poisson’s equation for the static charge distributed by the electronic structure of the CCD including the guard-rails etc. Then a dipole field which is supposed to be induced by the collected charge and an oppositely charged mirror charge in the CCD is superimposed on this field. The dipole field changes dynamically as the well fills. The strength of this dipole (as determined by the dipole length) governs the strength of the BF effect as implemented in PhoSim.

Discussion at the meeting revealed that the simple addition of a dipole field to the electrostatic one was likely non-realistic and other groups did either a full electrostatic calculation or a more complete series of image charge calculations in order to determine the proper field to implement. Work will soon begin to modify the PhoSim implementation of this effect. It should be stressed that the physical model which describes the BF effect is still being studied by the community.

Although phenomenological models such of that in [7] can fit observations, the true electrostatics of the system must be better understood and predictive models must be compared with lab-bench data.

2.1 Spots

In order to test the BF effect on a spot like source all other effects are turned off in PhoSim and a Gaussian spot with a width tuned to data sets at low light level is produced. A spot calibrated in photoelectron level is produced by determining the relationship between the PhoSim sky magnitude and the number of collected electrons on the CCD. Here a gain of one is assumed and the raw “electron-level” data is analyzed.

Spot intensities ranging from a few thousand electrons to 100,000 electrons are generated with a flat SED and then their width is extracted using the Sloan Digital Sky Survey shape measurement algorithm as implemented in the LSST software stack [11, 12]. The BF effect should cause the width of the spot to grow with it’s intensity. This procedure is repeated for many BF parameters ranging from no BF effect at all to 500 times the nominal PhoSim BF effect. The strength of the BF effect is modified by changing the length of the of the dipole induced by the extra charge in the model.

Currently, the PhoSim model assumes that all charge is held in the exact center of the pixel. Figure 1 shows the effect of this assumption on the lateral kick given to the drifting electron with arbitrary normalization from only the charge at the center of the pixel at nine different positions in the pixel. As can be seen charge drifting exactly to the center of the pixel (where the current charge is located) feels the largest effect.

In [6] Astier et al, found in data that the width of the spot grew by 2-3% over a similar range of intensities. The result of the phoSim simulation are shown in figure 2. In this figure, the widths in the X and Y direction are shown separately and the selected BF parameters range from no effect at all (“Perfect”) to 500 times the nominal. As can be seen, in order to obtain spot spreading at the 5% level, the size of the effect in the model must be increased to the order of 100 times the nominal.

The differences between the data and simulation in the case may be due to the unrealistic modeling of a pure dipole located exactly at the center of the pixel. We plan to modify the model of the charge and see if this improves the agreement.

2.2 Flats

As described in section 2, the BF effect should also affect the relationship between the variance and the mean of each pixel. Generally the ratio of these two quantities as a function of intensity is known as the Photon Transfer Curve (PTC) and can be used in the linear regime to extract the gain of the system. Non-linearities induced in the PTC by the BF effect was first described in detail in [5]. The authors of [5] also pointed out that if the non-linearity of the PTC was due to charge moving from one pixel to another then there should also be non-zero correlation coefficients between pixels, and further that grouping together pixels into larger blocks should mitigate the effect. In [6] this effect was measured in e2v LSST CCDs and a correlation coefficient of 1 to 5% was found to a pixel’s nearest neighbors. A larger coefficient was found in the y-direction presumably due to the presence of charge-stops impeding the transfer of charge in the x direction.

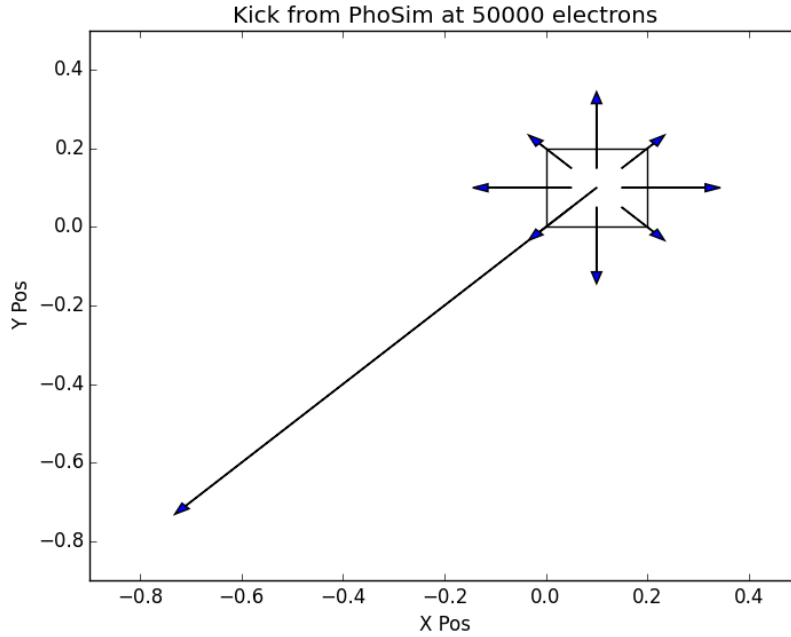


Figure 1. The kick in arcseconds due to the charge held in the center of a pixel imparted to an incoming electron when 50,000 electrons have already been collected. Each pixel (represented by the box in this figure) is $0.2''$ on a side in the LSST image plane. In PhoSim, the existing charge is modeled as being exactly in the center of the pixel. The nine arrows represent the kick imparted from the field of that charge to an electron at nine different points on the pixel. The field from other pixels and static charge in the CCD structure must also be included to determine the net displacement.

In order to test for this effect in PhoSim, I once again simulated calibrated levels of light on a photon-by-photon basis. In this case a flat illumination at 550 nm was simulated with electron levels ranging between 100 and 200,000 electrons per pixel for a set of BF strengths. All photon level optimizations are turned off in the simulation and so, in order to reduce computational run-time, the size of the simulated CCD is reduced from 4000×4000 to 400×400 pixels. Also, in order to remove any mean variations across the CCD plane caused by other effects (such as edge roll-off) two exposures were simulated and subtracted as in real data exposures, thus removing any common-mode effects.

First the PTC curve was examined. Figure 3 shows the common-mode subtracted mean/variance for with no BF effect applied along with the curve obtained with the nominal BF strength and ten times the normal dipole strength. As can be seen, with no effect the variance scales perfectly with the mean. The expected effect can be easily seen at one and ten times the nominal effect and, in the bottom panel, the results for the same analysis with the pixels ganged into 4×4 super-pixels is shown. As expected the size of the effect is reduced.

In order to qualitatively compare the results of the simulation with that of data reported in [6] I next calculated the spatial auto-correlation coefficient between each pixel and it's nearest neighbors on the subtraction of the two flat exposures. I then report horizontal correlation coefficient which is the average of the two nearest horizontal neighbor coefficients and a vertical coefficient

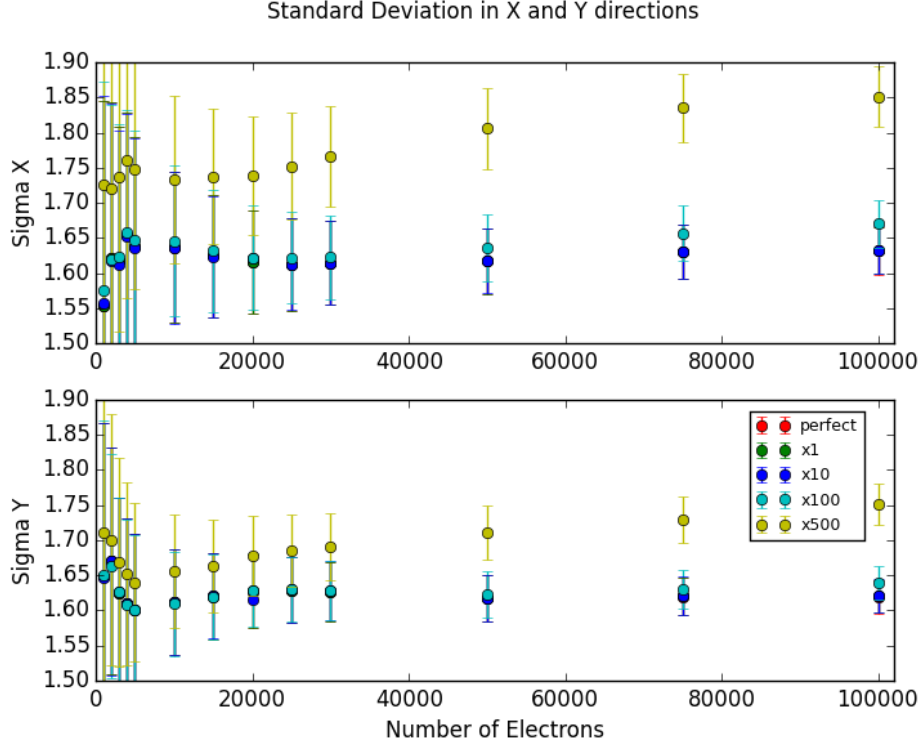


Figure 2. The measured X and Y width of the gaussian spot in pixels as a function of electron level for four different BF parameters ranging from no effect to 500 times the nominal PhoSim effect. The incoming Gaussian spot has a width of 1.6 pixels.

which is the average of the two nearest neighbor vertical coefficients. It should be noted that the correlation coefficient in this case is not position dependent but rather is the statistical calculation of the correlation coefficient of every pixel with its neighbors on one CCD.

The results of the simulation are shown in Figure 4 for both the horizontal and vertical coefficients. As expected with no BF effect, no correlation is seen. However at the nominal BF dipole magnitude we see about a 2% effect. This is very close to the size of the effect measured in data by [6].

2.3 Brighter Fatter Effect Conclusions

Somewhat surprisingly, we find that while the BF effect does not seem to be large enough when considering spot data compared to the previously reported data result in [6], it seems to match the data results well when measuring auto-correlation coefficients.

The first and most important caveat to consider is that the same algorithms I used to analyze the simulation data should be used to analyze real data. This is the only way to make a fair comparison. However, if the discrepancy between data and simulation still persists in that case it may be that the incomplete dipole model currently employed in PhoSim is the cause. More studies are necessary.

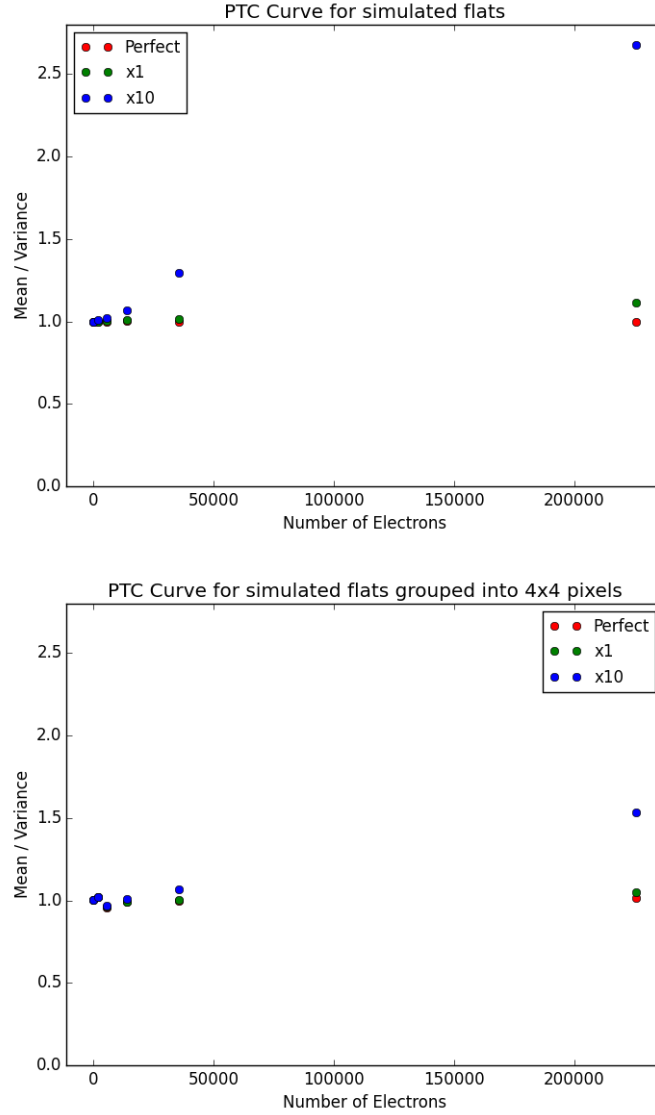


Figure 3. (Top) the common mode subtracted mean/variance as a function of electron level for three different BF parameters. (Bottom) the same result with pixels grouped into larger 4x4 blocks.

3. Edge Effects

Due to the presence of the guard rails in the CCD, electrons near the edge of the sensor feel a force which pulls them towards the edge. This manifests itself in a roll-off effect and an astrometric shift. We tested this effect in Phosim by making a grid of simple stars and moving them towards the edge of the sensor. Then, the `sExtractor` package [13] was used to measure their positions, and the astrometric shift was measured by comparing their true and measured positions. Figure 5 shows a comparison of the simulation data with lab data taken at BNL. These shapes are not the same which suggests that the surface charge contributions need to be tuned. The DECam's edge effect also does not entirely follow the behavior as expected by their model [10] which also implies

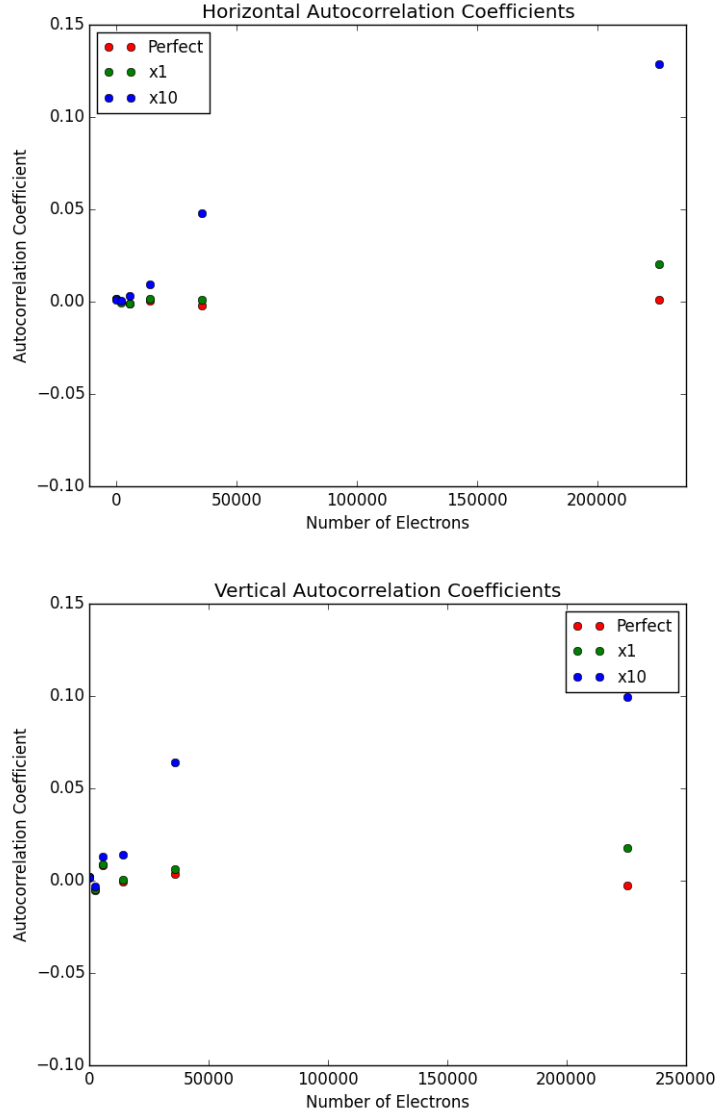


Figure 4. The horizontal (top) and vertical (bottom) auto-correlation coefficients between neighboring pixels for common mode subtracted pairs of exposures as a function of electron level for three different BF parameters.

that a better description of the charge distributions near the edge of the sensors is needed.

Additionally, in the process of doing the BF study I discovered a roll-off effect due to the BF effect itself. Namely, at least in the way we simulate the effect, it is possible for charge to be pushed off the edge of the chip by the fields present from already collected charge. On the other hand, this process does not work in the other direction. Due to the guard rail, charge from outside the sensitive region does not get pushed in. So, as you move towards the edge on a flat exposure, some of the charge is pushed out of the sensitive region resulting in a roll off.

Figure 6 show a comparison between the roll-off of spot data and flats in lab data taken at BNL. They behave differently. It is possible this is related to the BF related roll-off described above. We

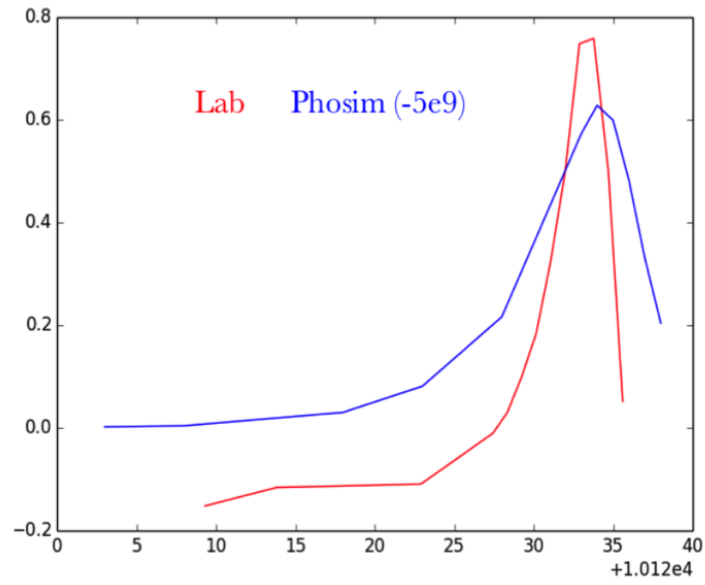


Figure 5. The astrometric shift as a function of linear position as a spot moves towards the edge of the sensor for both lab data (red) and PhoSim output (blue).

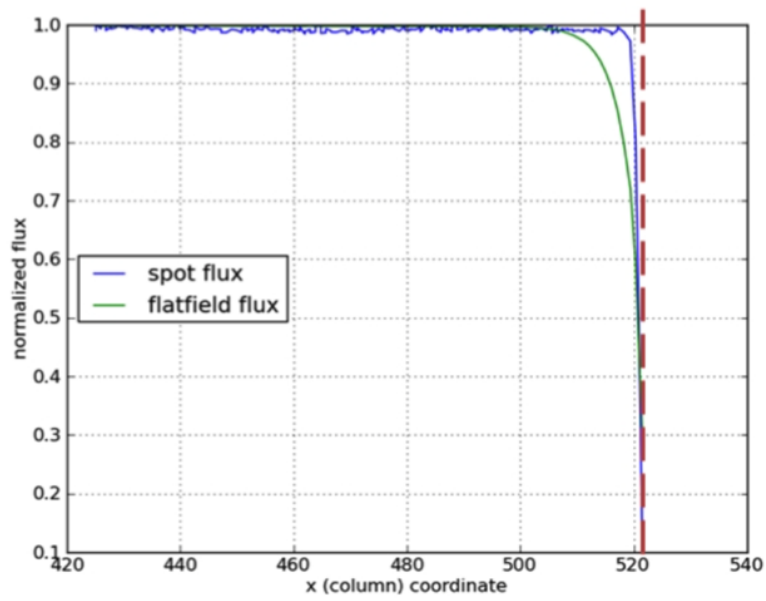


Figure 6. The decrease in measured flux as a function of CCD column coordinates for both a spot (blue) and a flat field (green).

need to further simulate and test these two configurations in order to draw conclusions.

4. Tree Rings

In the multi-day process of growing the silicon boules used to produce CCD sensors the doping intensity may vary as a function of time and thus position across the boule. The variations resemble “tree-rings” in their morphology and this gradient in doping concentration induces lateral fields inside the CCD which can distort shapes of imaged objects as the electrons drift down to the charge buckets. Descriptions of the simulation of this effect in PhoSim can be found elsewhere in these proceedings [4].

5. Conclusions

We have begun a concerted research program to simulate and validate physics CCD effects using PhoSim and real data. Currently, the tree-ring simulation seems to be working well and we will now tune the parameters. A first-pass model for the science groups should be available within a few months of the publication of these proceedings.

On the other-hand, it seems as if the model we are using to simulate the BF effect still needs further work. Direct comparisons with lab bench data will happen soon and should help us to refine the model. Other effects in the CCDs will be explored after this work is completed. Eventually we will use this model to estimate the impact on weak lensing shear analysis from these instrumental systematics.

Acknowledgments

The author would like to acknowledge and thank Andrei Nomerotski, Benjamin Beamer and Max Duncan for contributions on the tree-ring and edge effects studies, John Peterson for his work and help in using the PhoSim package, and Robert Lupton for useful conversations regarding the overall LSST simulation and measurement strategy.

The author would also like to thank the PhoSim and LSST teams for general help with the LSST software stack, and Duke University and the DOE Office of Science for supporting this research.

References

- [1] Z. Ivezić et al. [LSST Collaboration], *LSST: from Science Drivers to Reference Design and Anticipated Data Products*, arXiv:0805.2366 [astro-ph].
- [2] J.R. Peterson et al., *Simulation of Astronomical Images from Optical Survey Telescopes Using a Comprehensive Photon Monte Carlo Approach*, In preparation (2015)
- [3] J.R. Peterson, *PhoSim: a code to simulate telescopes one photon at a time*, *JINST* **9** C04010
- [4] B. Beamer, *A study of astrometric distortions due to “tree rings” in CCD sensors using the LSST Photon Simulator*, These Proceedings
- [5] Mark Downing, Dietrich Baade, Peter Sinclair, Sebastian Deiries, Fabrice Christen, *CCD riddle: a) signal vs time: linear; b) signal vs variance: non-linear*, *Proc. SPIE 6276, High Energy, Optical, and Infrared Detectors for Astronomy II*, 627609 (June 15, 2006)

- [6] P Antilogus *et al*, *The brighter-fatter effect and pixel correlations in CCD sensors* JINST **9** C03048
- [7] A. Guyonnet, P. Astier, P. Antilogus, N. Regnault and P. Doherty, *Evidence for self-interaction of charge distribution in charge-coupled devices*, Astron. Astrophys. **575**, A41 (2015) [arXiv:1501.01577 [astro-ph.IM]].
- [8] A. Rasmussen, P. Antilogus, P. Astier, C. Claver, P. Doherty, G. Dubois-Felsmann, K. Gilmore and S. Kahn *et al.*, *A framework for modeling the detailed optical response of thick, multiple segment, large format sensors for precision astronomy applications*, Proc. SPIE Int. Soc. Opt. Eng. **9150**, 915017 (2014) [arXiv:1407.5655 [astro-ph.IM]].
- [9] D. Gruen, G. M. Bernstein, M. Jarvis, B. Rowe, V. Vikram, A. A. Plazas and S. Seitz, *Characterization and correction of charge-induced pixel shifts in DECam*, These Proceedings, arXiv:1501.02802 [astro-ph.IM].
- [10] A. A. Plazas, G. M. Bernstein and E. S. Sheldon, *Transverse electric fields' effects in the Dark Energy Camera CCDs*, JINST **9**, C04001 (2014) [arXiv:1403.6127 [astro-ph.IM]].
- [11] T. Axelrod, J. Kantor, R. H. Lupton and F. Pierfederici, *An open source application framework for astronomical imaging pipelines*, Proc. SPIE 7740, Software and Cyberinfrastructure for Astronomy, 774015 (2010)
- [12] G. M. Bernstein and M. Jarvis, *Shapes and shears, stars and smears: optimal measurements for weak lensing*, Astron. J. **123**, 583 (2002) [astro-ph/0107431].
- [13] E. Bertin and S. Arnouts, *SExtractor: Software for source extraction*, Astron. Astrophys. Suppl. Ser. **117**, 393 (1996).